Stress-based regulation of multicellular plant growth: a finite element modeling approach applied to planar leaf morphogenesis

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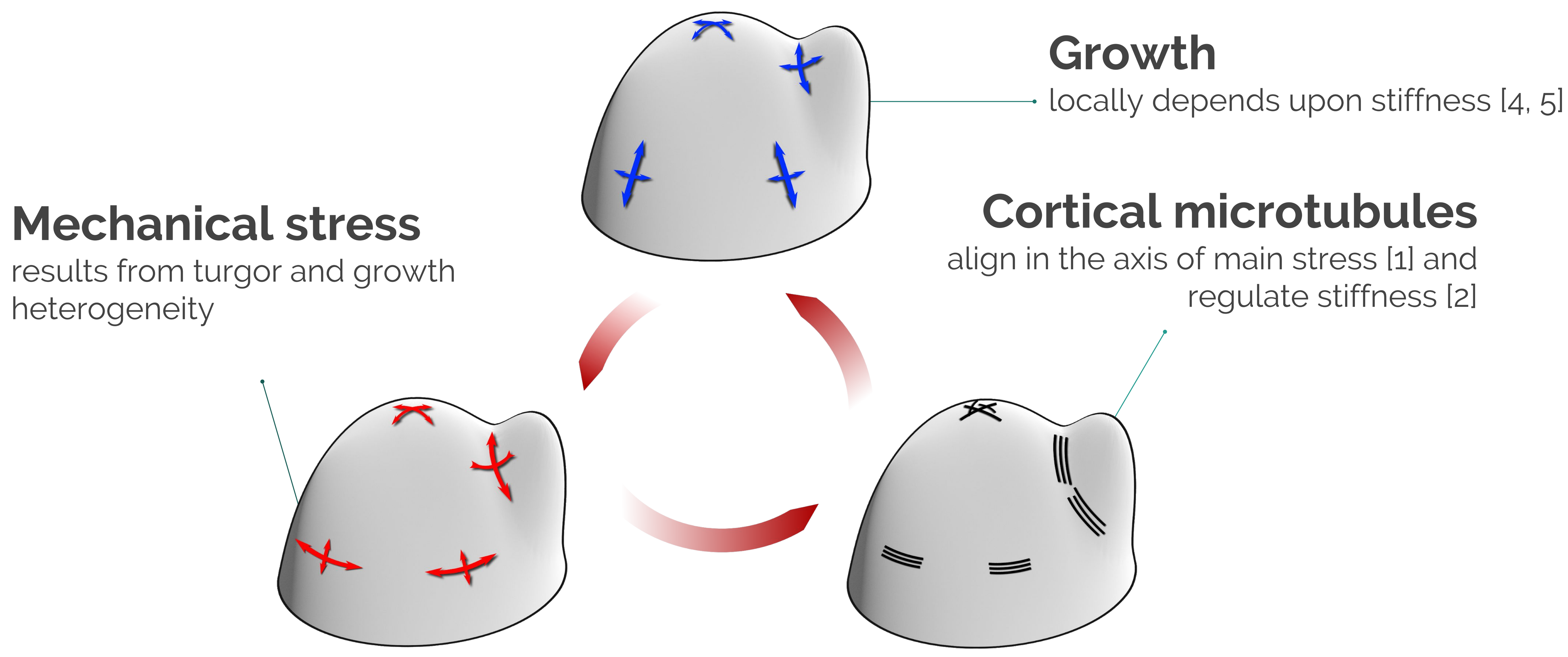
How do plant cells locally control their growth to coordinately produce macroscopic shapes?

➤ Mechanical tensions hypothetically provide cues governing local cell growth regulation [1,2].

What kind of emergent dynamical behavior can a stress-sensing tissue display?

➤ Finite element multicellular model coupling **growth** and **stress feedback**

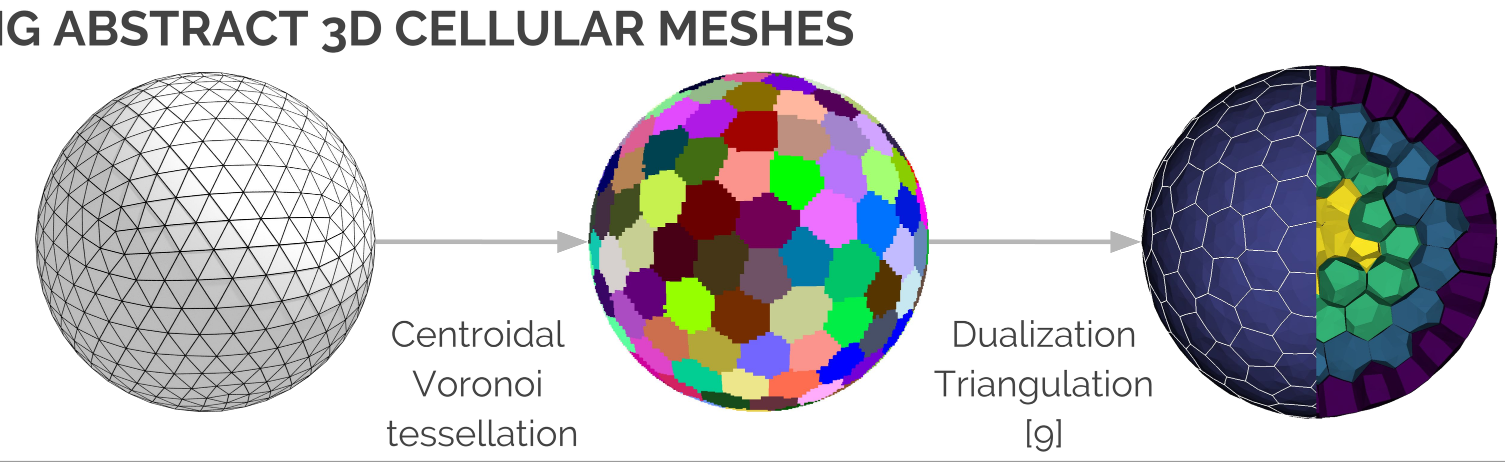


MODEL / SIMULATION LOOP

Mechanical equilibrium → Growth step → Microfibril dilution/rotation → Microfibril stress-regulated synthesis → Update stiffness → Compute new equilibrium

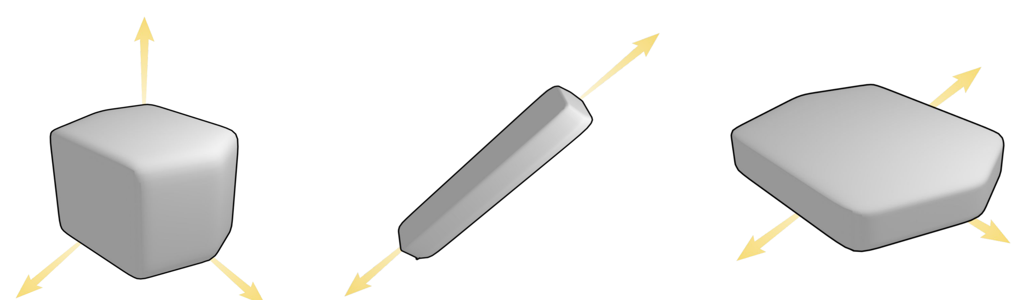
- Mechanical equilibrium: FEM (*Sofa* FW [6]) with pressurized structures
- Growth step: Update element rest state [4]: $\partial_t \boldsymbol{F}_g \propto (\boldsymbol{E} - \boldsymbol{E}_0)_+ \cdot \boldsymbol{F}_g$
- Microfibril dilution/rotation: Update microfibril angular density according to growth field
- Microfibril stress-regulated synthesis: Stress-dependent microfibril polym. [7] $\rho^+(\theta) \propto e^{\gamma S_\theta}$
- Update stiffness: Func. of low-frequency Fourier coef. of microfibril angular distribution [7, 8]

BUILDING ABSTRACT 3D CELLULAR MESHES



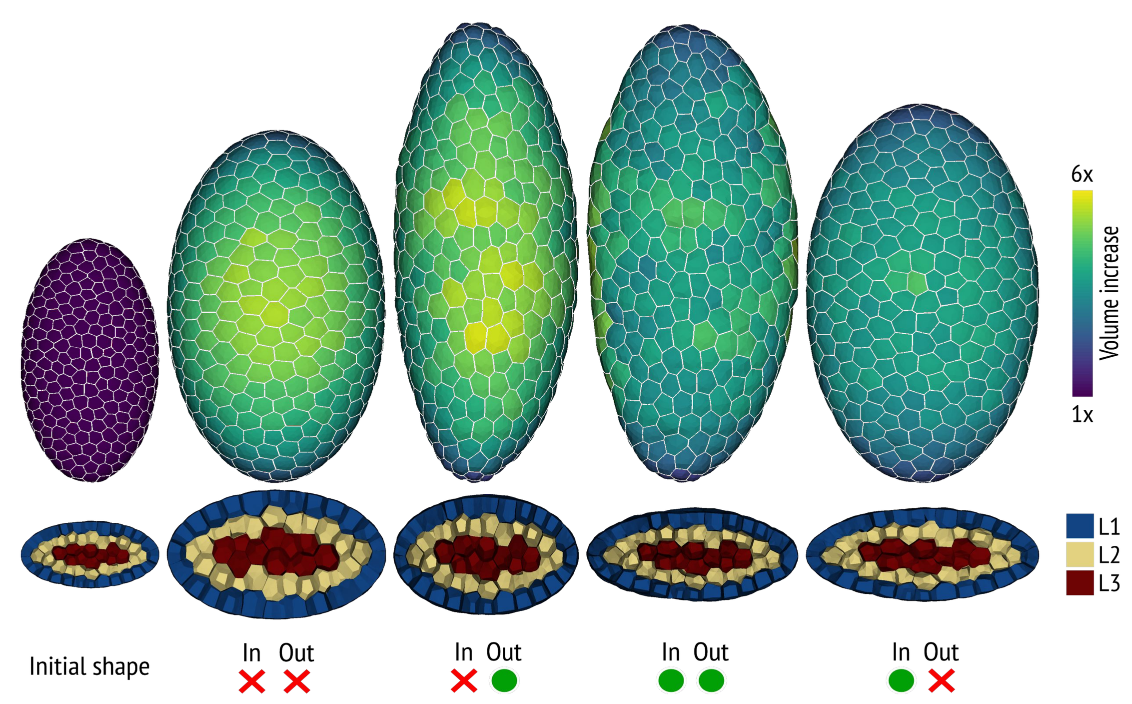
STABILITY OF PLANT GROWTH

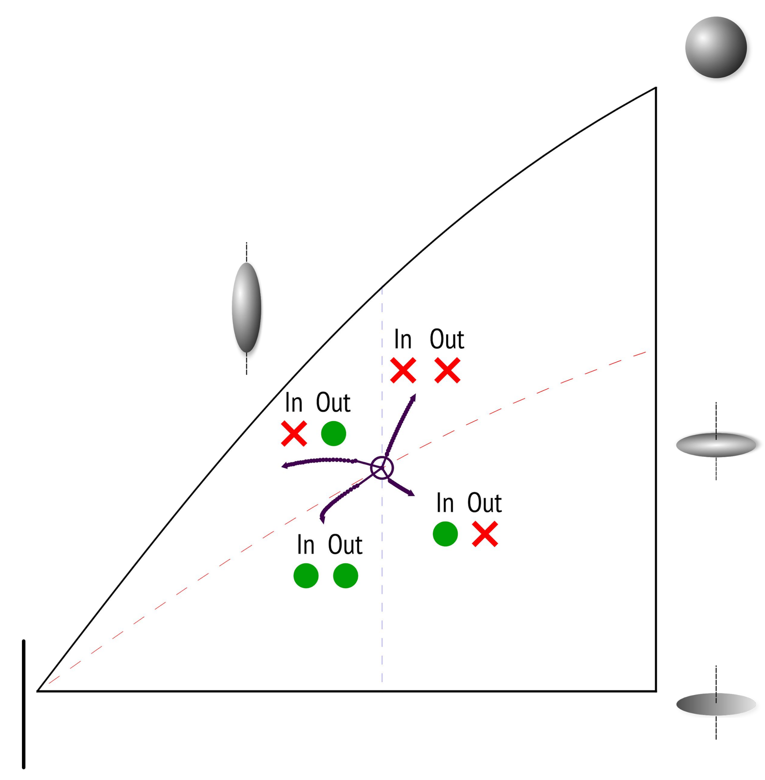
Several typical growth modes. Can a stress feedback mechanism capture them?



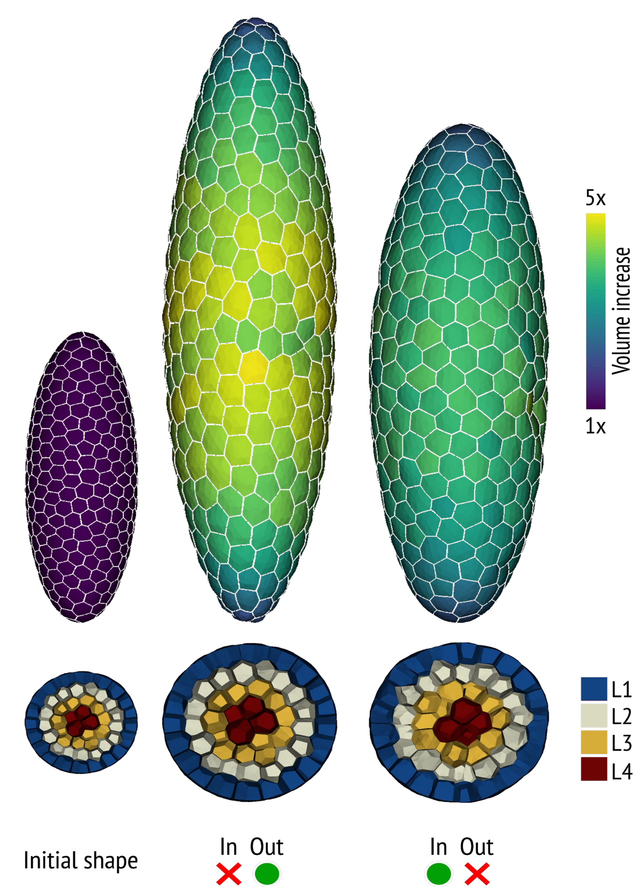
SOME RESULTS

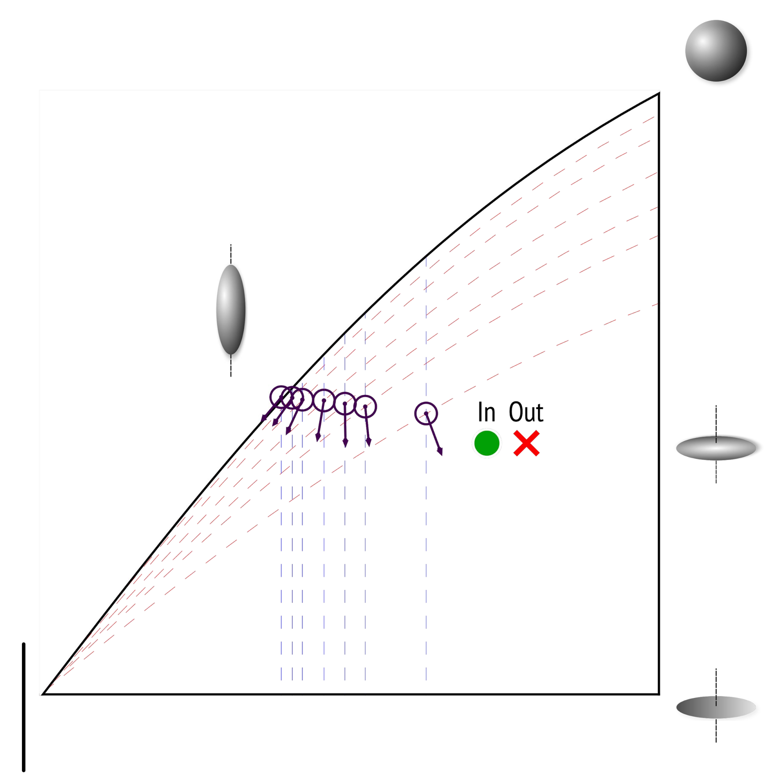
- We simulate the local dynamics of various abstract shapes (ellipsoids) mimicking flat shape (~800-cell meshes).
- Epidermal feedback or inner feedback stabilize axial elongation of axisymmetric shapes.
- Flat expansion requires inner stress feedback: microtubules align in the axis of thickness to resist thickening.
- This mechanism allows amplification of organ asymmetry.
- Coupling inner and epidermal feedback leads to conflicting microtubule alignment (not shown) → possible mechanical instability?





Morphospace





TAKE-HOME MESSAGE

A single mechanism accounts for flat and axial expansion mode depending on initial shape.

Coupling inner and epidermal stress feedback reveals nontrivial behavior and possibly unstable regimes. → Need for additional regulation?

References: **[1]** Hamant et al., 2008, Science; **[2]** Bozorg et al., 2014, PLOS Comp. Biol.; **[3]** Paredez et al., 2006, Science; **[4]** Boudon et al., 2015, PLOS Comp. Biol.; **[5]** Bozorg et al., 2016, Physical Biology; **[6]** Faure et al., 2012, in Soft Tissue Biomechanical Modeling for Computer Assisted Surgery. **[7]** Oliveri et al., 2018, J. of Mathematical Biology; **[8]** Cox, 1952; British J. of Applied Physics; **[9]** Cerutti et al., 2017, Frontiers in Plant Science.

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